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HERACLES and DJANGOH: Event Generation of *ep* Interactions at HERA Including Radiative Processes

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Abstract

Monte Carlo event simulation of neutral and charged current ep interactions at HERA with the event generators HERACLES and DJANGOH is described. The emphasis is put on the inclusion of radiative corrections, comprising single photon emission from the lepton or the quark line as well as self energy corrections and the complete set of one-loop weak corrections. The event generator HERACLES optionally treats the ep scattering either by means of structure function parametrizations or on the basis of parton distribution functions in the framework of the quark-parton model. The background from radiative elastic scattering $ep \to ep\gamma$ is also included. The event generator DJANGOH simulates deep inelastic lepton-proton scattering including both QED and QCD radiative effects. DJANGOH is an interface of the Monte Carlo programs HERACLES and LEPTO. Alternatively, parton cascades can be generated also with the help of ARIADNE. The LUND string fragmentation as implemented in the event simulation program JETSET is used to obtain the complete hadronic final state, provided there is enough hadronic mass. Otherwise, SOPHIA is used to generate low-mass hadronic final states.

1 Technical description

The computational procedures applied in HERACLES are based on the methods used in the AXO library [5] for Monte Carlo integration and event generation. AXO itself relies on the Monte Carlo integration algorithm VEGAS by P. Lepage [6]. The following steps have to be performed in actual computations:

1. Integration of the different contributions to be included. Thereby partial cross sections are determined according to the actually defined phase space region. They define the relative weight of the corresponding contribution in the final step of event sampling. Furthermore, the integration procedure supplies information for the construction of the distribution function applied for event generation. This step is controlled by input via code-words `'INT-OPT-NC'` and `'INT-OPT-CC'`, see subsection 3.1.1.

2. Estimation of the local maxima of the distribution function in a predefined number of hypercubes, needed since the integration volume is subdivided to optimize the rejection procedure. This step is usually executed together with the integration step 1. For applications where only cross sections are needed and no event generation is required, this step can be suppressed, see code-word `'INT-ONLY'`, subsection 3.1.1

3. According to the partial cross sections determined in step 1, events are then generated randomly from the individual contributions. In HERACLES, only the scattered lepton and sometimes a radiative photon is added to the event record. After construction of this part of the event, routines from DJANGOH are called to simulate QCD effects and to generate the hadronic part of the event. Control input for this step is transferred via code-words `'SAM-OPT-NC'` and `'SAM-OPT-CC'`, see subsection 3.1.1.

Steps 1) and 2) are necessary for each individual contribution to be included in the event generation. For flexibility (in particular with respect to CPU-time requirements) and test purposes the program allows a treatment of the different steps for each contribution separately. The information obtained in steps 1) and 2) is always written to an external file which has to be assigned in the corresponding run. If step 3) is done in a separate run of the program, a corresponding file has to be provided with information from steps 1) and 2). The random number seeds for refined integration by VEGAS or continued event sampling can also be stored on an external file. Conventions for file units are defined in subsection 3.3.1.

The user can communicate with the program by setting initial conditions (through input flags) and through a user analysis routine. The latter routine allows for *i*) additional initialization before generating events (for example booking of histograms), *ii*) analysis after having accepted an event and *iii*) a final call after completion of event generation. In the following section input flags will be documented while in section 3.2 the user analysis routine and common blocks used to store output of the program will be described.

1.1 Input to the program

The input to DJANGOH consists of two parts: the first part deals with HERACLES options and the second one contains DJANGOH input flags. The two parts are separated by the code word `'START'` in the sequence of input items. The format for the input in the two parts is the same as for HERACLES, i.e. an option card defining the expected information (`FORMAT (A10)`) is followed by one card containing the appropriate data (format-free – `READ(5,*)`). All data items except `'START'` (in the HERACLES part) and `'CONTINUE'` (in the DJANGOH part) are optional and are set to default values if they are not given as input. The sequence of different options within the two parts does not matter, only the `'CONTINUE'` option triggering the actual operation of the program has to be the last one.

In the following we describe the possible input options and the corresponding data expected by the program both for the HERACLES and the DJANGOH part. Default values are given in parentheses. For additional information concerning options of LEPTO 6.5.1 and JETSET 7.4 we refer to the corresponding manuals [10, 12].

1.1.1 HERACLES part

- `'TITLE'`
  data: user defined heading of the first output page.

- `'EL-BEAM'`
  data: `EELE`, `POLARI`, `LLEPT`
  quantities defining the properties of the lepton beam;

`EELE`	= energy of the lepton beam in GeV (D=27.6);
`POLARI`	= degree of beam polarization[1] (D=0.), $-1 \leq$ `POLARI` ≤ 1;
`LLEPT`	= lepton charge (D=–1),
	= -1, electron beam,
	= $+1$, positron beam.

- `'PR-BEAM'`
  data: `EPRO`
  properties of the proton beam;

  `EPRO` = energy of the proton beam in GeV (D=820.).

- `'KINEM-CUTS'`
  data: `ICUT`, `XMIN`, `XMAX`, `YMIN`, `YMAX`, `Q2MIN`, `Q2MAX`, `WMIN`
  definition of kinematical cuts. These cuts are applied to the *leptonic* variables x_l, y_l,

[1]The treatment of events in LEPTO may have problems for values above 0.99 or below -0.99.

Q_l^2, defined by the momentum of the final-state lepton, and the mass of the hadronic final state.

`ICUT` $= 1$: cuts in x_l and lower cut in Q_l^2 (`Q2MIN` in GeV^2), cuts in y_l are ignored,

$= 2$: cuts in x_l, lower cut in Q_l^2 and lower cut in the hadronic mass W_h (`WMIN` in GeV), cuts in y_l are ignored,

$= 3$: cuts in x_l, y_l, Q_l^2 and W_h.

Default values: `ICUT` $= 3$, `XMIN` $= 10^{-3}$, `XMAX` $= 1.0$, `YMIN` $= 10^{-2}$, `YMAX` $= 1.0$, `Q2MIN` $= 4.0$, `Q2MAX` $= 10^8$, and `WMIN` $= 5.0$. The final definition of cuts according to the most restrictive conditions is performed in the subroutine `HSPRLG`.

- `'THETA-CUT'`
  data: `THEMIN`
  lower cut on the lepton scattering angle in *rad* with respect to the incoming lepton (D=0.).

- `'PT-CUT'`
  data: `PTMIN`
  lower cut on the transverse momentum of the scattered lepton in GeV (D=0.).

- `'EGAM-MIN'`
  data: `EGMIN`
  definition of a lower cutoff energy for bremsstrahlung photons (in GeV);

  `EGMIN` $= 0.0$: Both radiative and non-radiative events are generated. The separation of the cross section into non-radiative and radiative parts with the help of a soft-photon cutoff is determined internally as a function of x and y. This option has to be used if integration/sampling of both radiative and non-radiative channels is requested.

  `EGMIN` > 0.0: Only hard-photon bremsstrahlung (with energy above `EGMIN`) is considered for event sampling (in this case the data items `ISNC2` and `ISCC2` from input options `'SAM-OPT-NC'` and `'SAM-OPT-CC'` are ignored!).

  Default: `EGMIN` $= 0$.

- `'THMIN-QRAD'`
  data: `TCUTQ`, `TCUTQS`
  definition of cuts for the separation of photons from the incoming and outgoing quarks (in *rad*, defaults: `TCUTQ=TCUTQS` $= 0.25$).

- `'GSW-PARAM'`
  data: `LPARIN(1:11)`
  monitoring the definition of electroweak parameters and the inclusion of different virtual corrections;

`LPARIN(1)`	$= 1$:	electroweak parameters set with fixed values for the boson masses M_W, M_Z,
	$= 2$:	electroweak parameters calculated from fixed M_Z, G_μ.

Default: `LPARIN(1)` = 2. The definition of boson and fermion masses as far as they are not input from code word `'GSW-MASS'` and the calculation of coupling constants is done in the subroutine `HSSETP`.

`LPARIN(2)`	$= 0$:	only Born cross section without electromagnetic or weak corrections is integrated/sampled,
	$= 1$:	Born cross section including corrections as determined by the values of `LPARIN(3)` – `LPARIN(11)`.

Default: `LPARIN(2)` = 1.
The following options define the corresponding corrections to be included in the actual calculation (0 / ≥ 1 = no / yes):

`LPARIN(3)` (D=3) :		flag for inclusion of higher order contributions:
	$= 0$:	no higher order corrections,
	≥ 1 :	terms of $\mathcal{O}(\alpha^2 m_t^4)$ included,
	≥ 2 :	terms of $\mathcal{O}(\alpha\alpha_s m_t^2)$ included,
	≥ 3 :	running $\alpha(Q^2)$ is used for the radiative cross section ;
`LPARIN(4)` (D=1) :		leptonic QED corrections;
`LPARIN(5)` (D=0) :		quarkonic QED corrections;
`LPARIN(6)` (D=0) :		lepton-quark interference[2];
`LPARIN(7)` (D=2) :		fermionic contributions to the photon self energy Σ^γ:
	$= 0$:	not included,
	$= 1$:	parametrization with the help of quark masses,
	$= 2$:	parametrization from [20];
`LPARIN(8)` (D=0) :		fermionic contribution to the $\gamma - Z$ mixing;
`LPARIN(9)` (D=0) :		fermionic contribution to the self energy of the Z boson;
`LPARIN(10)` (D=0) :		fermionic contribution to the self energy of the W boson;

[2]The contribution from lepton-quark interference can be requested only if both the leptonic and the quarkonic corrections are activated at the same time.

`LPARIN(11)` (D=0) : purely weak contributions to the self energies, vertex corrections and boxes.

- `'GSW-MASS'`
  data: `MW`, `MZ`, `MH`, `MT`
  the electroweak mass parameters: W and Z boson masses, Higgs mass and the top-quark mass (in GeV). The value given for `MW` is used only if at the same time `LPARIN(1)` = 1. Otherwise, M_W is calculated in the program from the μ decay constant. The defaults are $M_Z = 91.1867$ GeV, $M_H = 150$ GeV and $m_t = 175$ GeV.

- `'STRUCTFUNC'`
  data: `ILQMOD`, `ILIB`, `ICODE`
  defines the parametrization of parton densities or structure functions applied in the calculation. `ILQMOD` encodes options for the treatment of structure functions in the low Q^2 region, `ILIB` defines a library of subroutines to be used for the calculation of parton distribution or structure functions and the corresponding parametrization is specified by `ICODE`. The parton distribution functions are taken via the modified LEPTO routine `LYSTFU` from PYTHIA (routine `PYSTFU`) [21]. The switches `ICODE` and `ILIB` agree with the PYTHIA parameters `MSTP(51)` and `MSTP(52)`. The meaning of `ICODE` depends on the value of `ILIB`. The allowed values are as follows:

  `ILIB` = 1 : to choose parton distribution functions from the PYTHIA routine `PYSTFU`;

  `ICODE` = 1 : Eichten et al., set 1 (1986 update) [22],
  = 2 : Eichten et al., set 2 (1986 update) [22],
  = 3 : Duke/Owens, set 1 [23],
  = 4 : Duke/Owens, set 2 [23],
  = 5 : CTEQ2M (best $\overline{\mathrm{MS}}$ fit) [24],
  = 6 : CTEQ2MS (singular at small x) [24],
  = 7 : CTEQ2MF (flat at small x) [24],
  = 8 : CTEQ2ML (large Λ) [24],
  = 9 : CTEQ2L (best leading order fit), [24],
  = 10: CTEQ2D (best DIS fit) [24],

  `ILIB` = 2 : to use PDFLIB [25]. Calls are performed via `PYSTFU` and the user has to link the corresponding library;

  `ICODE` = 1000∗`NGROUP` + `NSET`, the identification code for the parametrization of parton distribution functions for PDFLIB (version 4);

ILQMOD = 0: use unmodified parton distribution functions for all Q^2.

ILQMOD = 1: apply exponential low Q^2 suppression factor to parton distribution functions[26].

The following options are available only in the HERACLES mode:

ILQMOD = 2: for low Q^2 (for $Q^2 < 6$ GeV^2) use F_1 and F_2 parametrizations from Brasse [27] (for $W < 2$ GeV) and Stein [28] (for $W > 2$ GeV). For large Q^2, parton distribution functions as determined by ICODE are used.

ILQMOD = 3: for $Q^2 < 6$ GeV^2 use parametrizations from Abramowicz, Levy, Levin, and Maor [29] (for $W > 2$ GeV) together with Brasse (for $W < 2$ GeV). If ICODE = 0, the ALLM parametrization is used for high Q^2 as well; if ICODE $\neq 0$, for large Q^2 the parton distributions as requested by ICODE are combined with the ALLM parametrization.

ILQMOD = 4: For $x < 0.1$ and $\nu > 10$ GeV, the parametrization by Badełek and Kwieciński [30] is used. For $\nu < 10$ GeV, $x < 0.1$, the Brasse and Stein parametrization is used. At larger x, the parton distribution functions from MRS, set D'_- [31] have to be used. NOTE: other combinations of BK with PDF's are inconsistent! It is recommended to use ILQMOD = 4 together with ICODE = 0, in which case the MRS D'_- set is automatically chosen.

ILQMOD = 5: The Donnachie–Landshoff parametrization [33] for $Q^2 < 10$ GeV^2 together with parton distribution functions are used. If ICODE = 0, the set MRS $B235$ [32] is chosen, since this gives the smallest discontinuities of the cross section.

The default values are `ILQMOD` = 1 (exponential low Q^2 suppression), `ILIB` = 2 (PDF's from `PDFLIB`) and `ICODE` = 3041 (MRS(G)), i.e. `ISTRFC` = 123041. The user himself is responsible for giving consistent input. For example, the recent MRS(A) parametrizations (provided via PDFLIB, e.g.) should not be combined with `ILQMOD` = 1, since these parametrization already contain a prescription for the small-Q^2 behaviour which ensures the correct limit for the structure functions.

- `'NUCLEUS'`
  data: `EPRO, HNA, HNZ`
  for lepton nucleon scattering. `EPRO` is the energy per nucleon in the beam (in GeV), `HNA` and `HNZ` are atomic and charge numbers of the nucleon
  Defaults: `HNA = HNZ` = 1.

- `'EP-DIPOLE'`
  data: `IDIPOL`

to include (if non-zero) the parametrization of [28] for the deviation of the elastic *ep* form factors from the simple dipole form.
Default: `IDIPOL` = 0.

- `'FLONG'`
  data: `IFLOPT`, `PARL11`, `PARL19`
  for the inclusion of the longitudinal structure function F_L. The definition of `IFLOPT` coincides with the definition of `LST(11)` of LEPTO 6.5.1 [10]:

  ```
  IFLOPT = LQCD + LTM*10 + LHT*100
  ```

  and `LQCD`, `LTM` and `LHT` specifies whether QCD contributions, target mass effects and higher twist should be included. See the manual of LEPTO 6.5.1 [10] for details. HERACLES calls modified routines from LEPTO 6.5.1 to calculate F_L either event-by-event when `LQCD` = 2 or `LTM` = 2 (time-consuming) or by using a grid and linear interpolation for `LQCD` = 1 or `LTM` = 1.
  For the calculation of radiative corrections, F_L is needed for small Q^2, also in the limit $Q^2 \to 0$. The prescription for $F_L(Q^2 \to 0)$ is determined by `ILQMOD`. In the interface with DJANGOH this means that F_L is calculated from perturbative QCD. For Q^2 values smaller than $Q_0^2 = 6$ GeV^2, F_L is assumed to be independent of Q^2 and its value is given by $F_L(Q^2 = Q_0^2)$.
  The meaning of the parameters `PARL11` and `PARL19` coincides with that of `PARL(11)` and `PARL(19)` in LEPTO 6.5.1:

`PARL11` :	Accuracy for the integration needed to calculate F_L;
`PARL19` :	κ^2, the scale parameter for higher-twist contributions in F_L.

  The default values are `IFLOPT` = 0, `PARL11` = 0.01, `PARL19` = 0.03.

- `'ALFAS'`
  data: `MST111`, `MST115`, `PAR111`, `PAR112`
  information defining the value of α_s needed for the inclusion of F_L. α_s enters the calculation of F_L and is evaluated in the routine `ULALPS` from JETSET 7.4. The meaning of the input data corresponds to the parameters `MSTU(111)`, `MSTU(115)`, `PARU(111)`, `PARU(112)` of JETSET 7.4 and is as follows:

`MST111` :	Order of α_s evaluation in `ULALPS`: = 0: fixed α_s at the value of `PAR111`, = 1: first-order running α_s, = 2: second-order running α_s, (D=1);
`MST115` :	Treatment of the α_s singularity at $Q^2 \to 0$: = 0: allow it to diverge like $1/\ln(Q^2/\Lambda^2)$, = 1: soften the divergence to $1/\ln(1 + Q^2/\Lambda^2)$, = 2: freeze Q^2 evolution below $Q_0^2 = 4$ GeV^2, (D=0);

PAR111 : The fixed value of α_s assumed in ULALPS when MST111 = 0 (D=0.20);

PAR112 : Λ used in running α_s in ULALPS (D=0.25).

- 'NFLAVORS'
  data: NPYMIN, NPYMAX
  minimal and maximal number of flavors to be included in the cross section. The flavors are counted from 1 to 6 in the following order: d, u, s, c, b, and t. Defaults are NPYMIN = 1 and NPYMAX = 6.

- 'INT-ONLY'
  data: INTOPT
  A negative value for INTOPT supresses the call to subroutines needed for the preparation of the sampling steps. Only integration of the differential cross section is performed in this case. Default: 0.

- 'INT-OPT-NC'
  data: INC2, INC31, INC32, INC33, INC34, IEL2, IEL31, IEL32, IEL33
  defines the contribution(s) to neutral current interactions for which the integrated cross section is asked to be calculated in order to prepare the sampling procedure (including estimation of local maxima of the actual distribution function if INTOPT ≥ 0):

  INC2 : Integration for the **non-radiative contribution** (Born term including virtual and soft corrections); integration by Gaussian quadrature, NAGLIB routine D01FCF,

  INC31 < 100: number of iterations for integration of the contribution from **initial state leptonic bremsstrahlung** by VEGAS,

  INC31 > 100: (INC31-100) iterations by VEGAS1; here the iteration procedure is restarted to estimate the integral; the grid structure is used from the previous run, but estimates of the integral and its error accumulated in the previous run(s) are discarded. The necessary information is read from an external file which had to be defined before by a run with INCx < 100,

  INC31 > 200: (INC31-200) iterations by VEGAS2: the iteration procedure is restarted using both the grid information and the accumulated estimates of the integral and its error from the previous run(s);

  INC32 : monitoring the integration of **final state leptonic bremsstrahlung** with the same conventions as for INC31;

  INC33 : monitoring the integration of **the Compton contribution** with the same conventions as for INC31;

INC34 :	monitoring the integration of **the contribution from radiation from the quark line** with conventions as for INC31 (not active in DJANGOH);
IEL2 :	monitoring the integration of **elastic scattering** $ep \to ep$ with conventions as for INC2;
IEL31 :	for the integration of the quasielastic tail $ep \to ep\gamma$ from **initial state leptonic bremsstrahlung**,
IEL32 :	for the integration of the quasielastic tail $ep \to ep\gamma$ from **final state leptonic bremsstrahlung**,
IEL33 :	for the integration of the quasielastic tail $ep \to ep\gamma$ from the **Compton contribution**,

Defaults are INC2=INC31=INC32=INC33=INC34 = 0 and IEL2=IEL31=IEL32=IEL33 = 0, no integration.

- 'INT-OPT-CC'
  data: ICC2, ICC31, ICC32, ICC33
  same as 'INT-OPT-NC' but for the charged current interaction:

ICC2 :	Integration for the non-radiative contribution (Born term with virtual and soft corrections);
ICC31 :	Integration of the contribution from 'leptonic initial state' bremsstrahlung by VEGAS;
ICC32 :	Integration of the contribution from 'quarkonic initial state' radiation (not activated);
ICC33 :	Integration of the contribution from the 'quarkonic final state' radiation (not activated).

Defaults are ICC2=ICC31=0, no integration.

- 'INT-POINTS'
  data: NPOVEG
  upper limit for the number of integration points used by VEGAS (D=10000).

- 'HYP-CUBES'
  data: NPHYP
  the number of points in each bin used to estimate the function maxima (D=20).

- 'SAM-OPT-NC'
  data: ISNC2, ISNC31, ISNC32, ISNC33, ISNC34, ISEL2, ISEL31, ISEL32, ISEL33
  monitoring the inclusion of individual contributions to the neutral current cross section for event sampling. A contribution is included if the corresponding option is set to 1 or 2, resp.; ISNCx = 2 triggers continued sampling, i.e. information from a previous sampling run with ISNCx $\neq 0$ is expected:

ISNC2 : non-radiative contribution;

ISNC31 : initial state leptonic bremsstrahlung;

ISNC32 : final state leptonic bremsstrahlung;

ISNC33 : Compton contribution;

ISNC34 : quarkonic radiation.

ISEL2 : elastic scattering $ep \to ep$;

ISEL31 : initial state leptonic radiation for $ep \to ep\gamma$;

ISEL32 : final state leptonic radiation for $ep \to ep\gamma$;

ISEL33 : Compton contribution for $ep \to ep\gamma$;

Defaults: ISNCx = 0.

- 'SAM-OPT-CC'
  data: ISCC2, ISCC31, ISCC32, ISCC33
  same as 'SAM-OPT-NC' but for the charged current. For the physical content of the charged current radiative channels, see option 'INT-OPT-CC'. Defaults: ISCCx = 0.

- 'WEIGHTS'
  data: IWEIGS
  generation of events with externally defined weight function;

  IWEIGS = 0: Events are generated according to the true differential cross section calculated by the program including or excluding radiative corrections as requested by the user input;

  IWEIGS = 1: Events are generated according to the differential cross section modified by the additional weight factor

$$\omega = x_l;$$

  IWEIGS = 2: Events are generated according to the differential cross section modified by the additional weight factor

$$\omega = \begin{cases} Q_l^2/Q_0^2 & \text{for } Q_l^2 \leq Q_0^2 = 100\,\mathrm{GeV}^2, \\ 1 & \text{for } Q_l^2 \geq Q_0^2. \end{cases}$$

  Other weight functions, which may depend on the lepton kinematic variables x_l and y_l, can be defined by the user in the routine HSWGTX. Default: IWEIGS = 0.

- 'RNDM-SEEDS'
  data: ISDINP, ISDOUT
  monitoring input/output of actual random seeds from/to unit LUNRND:

  ISDINP = 0/1 : (no) input of seeds;

ISDOUT = $0/1$: (no) output of seeds;

default: ISDINP = ISDOUT = 0.

- 'IOUNITS'
  data: LUNOUT, LUNRND, LUNDAT
  logical unit numbers for in- and output:

  LUNOUT: for standard output (D=6);

  LUNRND: for in-/output of the random number status from/to an external file (D=10);

  LUNDAT: for in-/output of results from the integration step from/to an external file (D=11).

- 'START'
  data: NEVENT
  starts the execution of the main program;

  NEVENT : number of requested events if any sampling option is activated (D = 0).

1.1.2 DJANGOH part

In the following we describe input options which determine the treatment of QCD effects in the DJANGOH, resp. LEPTO part of the program. Only a few selected flags are allowed as explicit input items. Other flags can be changed in the block data subroutine LEPTOD. Exceptions are the flags LST(1), LST(2), LST(6), LST(17), and LST(18) which must not be changed in order that DJANGOH works correctly.

- 'OUT-LEP'
  data: LST(4) (integer, D=1)
  regulates which information is written onto the event record:

  LST(4) = $\mathrm{I}_{lepton} + 10{*}\mathrm{I}_{shower}$;

  $\mathrm{I}_{lepton} = 0/1$ inactive/active scattered lepton;

  $\mathrm{I}_{shower} = 0/1$ exclude/include intermediate partons.

- 'FRAME'
  data: LST(5) (integer, D=3)
  choice of frame for the event:

  LST(5) = 1: hadronic cms frame, z-axis along boson,

  = 2: ep cms frame, z-axis along lepton,

= 3: *ep* lab system, z-axis along lepton,

= 4: *ep* lab system, z-axis along exchanged boson.

- `'FRAG'`
  data: `LST(7)` (integer, D=1)

`LST(7)` = -1: no generation of parton cascades and no fragmentation,

= 0: event generation at the parton level, no hadronization,

= 1: event generation including hadronization and decays of unstable particles.

- `'CASCADES'`
  data: `LST(8)` (integer, D=12)
  describes that part of the event simulation which is determined by perturbative QCD:

`LST(8)` = 0: no QCD effects, i.e. no gluon radiation or boson-gluon fusion,

= 1: including QCD processes (gluon radiation and boson-gluon fusion) according to the first-order matrix elements,

= 2: QCD parton cascade evolution of initial and final quark,

= 3: QCD parton cascade evolution of initial quark only,

= 4: QCD parton cascade evolution of final quark only,

= 5: QCD switched off, but target treatment exactly as in parton cascade case,

= 9: simulating QCD cascades in the colour dipole model as implemented in ARIADNE,

= $12-15$: as $2-5$, but parton shower added to the event as obtained from first-order matrix elements (ME+PS).

- `'MAX-VIRT'`
  data: `LST(9)` (integer, D=5)
  maximal virtuality in parton cascades (active only for `LST(8)` $= 2-5$):

`LST(9)` = 1: Q^2,

= 2: W^2,

= 3: $W \times Q$,

= 4: $Q^2 \times (1-x)$,

= 5: $Q^2 \times (1-x) \times max(1, \ln(1/x))$,

= 6: $x_0 W^2$,

= 9: $W^{4/3}$, i.e. similar as in the colour dipole model.

- 'BARYON'
  data: `LST(14)` (integer, D=4)
  treatment of the target remnant (for more detailed information, see [10]):

  `LST(14)` = 0: baryon production from remnant excluded,

  = 1: baryon production from remnant included,

  = 2, 3: as 1 but with different energy-momentum fractions distributed over remnant parts;

  = 4: using LUZDIS [12].

- 'KT-PARTON'
  data: `PARL(3)` (real, D=0.44)
  width of Gaussian primordial transverse momentum distribution (in GeV).

- 'DIQUARK'
  data: `PARL(4)` (real, D=0.75)
  probability that a ud-diquark in target remnant has spin and isospin equal to zero, i.e. I=S=0.

- 'KT-REMNANT'
  data: `PARL(14)` (real, D=0.35)
  width of Gaussian p_T when non-trivial target remnant is split into a particle and a jet (in GeV).

- 'AR-REMNANT'
  data: `MSTA(30)` (integer, D=1)
  extendedness of initial partons in ARIADNE (see [11]);

  `MSTA(30)` = 0: struck quark is pointlike and proton remnant extended with $\mu =$ `PARA(11)` (= 1 GeV by default), where μ is the inverse extension of the proton remnant,

  = 1: as for 0 but $\mu =$ `PARA(11)`$/(1-x)$,

  = 2: as for 1 but also struck quark is extended with $\mu = \sqrt{Q^2}$.

- 'SOPHIA'
  data: `WSOPHIA` (real, D=1.5)
  defines the upper limit for the hadronic mass, below which SOPHIA [34] is used to generate the hadronic final state.

- 'CONTINUE'
  continue execution of the main program, start event generation.

1.2 Output

1.2.1 Standard output

All quantities transferred to the program via the input options are echoed immediately after reading the input. The final definition of all important parameters is printed before the actual start of the integration/sampling procedure. The results of the integration step are:

(i) Non-radiative contribution:
The resulting estimate of the integrated non-radiative cross section and an estimate for its error is printed; (presently requested relative accuracy $\Delta I/I = 10^{-3}$).

(ii) Bremsstrahlung contributions:
The program gives the standard output generated by the VEGAS routines, including

- number of function evaluations per iteration;
- integral and error estimates for the actual iteration;
- accumulated integral and error estimates taking into account results from previous iterations (depending on the entry chosen for the VEGAS routine, compare input option 'INT-OPT-NC').

After event sampling, the actually applied cross sections and the numbers of generated events are given for each individual contribution. For each run, a header record and a terminating record is written to the common block /HEPEVT/ according to the standards proposed in [35]. The header record contains in addition to the standard quantities parameter definitions and option flags, the final record includes some partial results. Details are given in appendix B.

1.2.2 Event record and User's analysis

Any user action is expected in the user supplied subroutine `HSUSER(ICALL,X,Y,Q2)`. The routine allows for user action in three different phases of running DJANGOH:

- before generating events (`ICALL=1`),
- after each generated event (`ICALL=2`),
- after completion of event generation (`ICALL=3`).

The arguments `X`, `Y`, `Q2` correspond to the lepton kinematic variables of the actual event.

For each sampled event the information about the $eq \to eq(\gamma)$ subprocesses is transferred to `HSUSER` via the HERACLES common blocks `/HEPEVT/`, `/HSIKP/` and `/HSCHNN/`. The

information about the hadronic final state is contained in the common block `/LUJETS/` of JETSET 7.4 [12]. In case of an event with hard QED bremsstrahlung, the information about the radiated photon is found in `/LUJETS/` right after the scattered lepton, i.e. in line 5. Additional information is contained in the common blocks `/DJPASS/` and `/LEPTOU/` (of LEPTO). Below we describe those common blocks which can be useful for the analysis of the event. For details about the content of the common block `/LUJETS/` which contains the event record we refer the reader to the manual of JETSET 7.4 [12].

The event record is also stored on the common block `LUJETS` when the hadronization step failed (or was not attempted, as in the case of QED Compton events). In this casem the event record contains, besides the scattered electron and a potential bremsstrahlung photon, the scattered quark and the proton remnant.

1.2.3 Common block LEPTOU

```
COMMON /LEPTOU/ CUT(14),LST(40),PARL(30),X,Y,W2,Q2,U
```

Content: contains input switches (`LST(1)` – `LST(20)`) and input parameters (`PARL(1)` – `PARL(20)`) for LEPTO to specify physics, kinematic cuts and numerical procedures, as well as output flags (`LST(21)` – `LST(40)`) and output variables (`PARL(21)` – `PARL(30)`). Many of the input flags and parameters are initialized in HERACLES. Additional ones are determined either through explicit input of DJANGOH or by default values in `BLOCK DATA LEPTOD`. Some switches of LEPTO are not optional anymore in DJANGOH, but have to be kept fixed at values given in the list below.

Parameters:

`CUT(1)` – `CUT(14)`: lower and upper limits on x_l, y_l, Q_l^2, W_h^2, ν, E', θ'; included for documentation purposes only (passed from HERACLES).

`LST(1)` : (D=2) not optional: independent variables are x and y;

`LST(2)` : (D=3) not optional: scaled variables $(\tilde{x}, \tilde{y})$ passed via `LEPTOU`;

`LST(3)` : (D=2) only warnings printed, execution stopped on error;

`LST(4)` : (D=1) user input via code-word `'OUT-LEP'`, cf. section 3.1.2;

`LST(5)` : (D=3) user input via code-word `'FRAME'`, cf. section 3.1.2;

`LST(6)` : (D=0) not optional: no rotation of the azimuthal angle, ϕ, of the lepton scattering plane; random azimuthal orientation passed from HERACLES;

`LST(7)` : (D=1) user input via code-word `'FRAG'`, cf. section 3.1.2;

=0: parton level events generated, optionally including QCD effects according to `LST(8)`;

=1: full event generated, i.e. including hadronization and decays;

`LST(8)` : (D=12) user input via code-word `'CASCADES'`, cf. section 3.1.2;

`LST(9)` : (D=5) user input via code-word `'MAX-VIRT'`, cf. section 3.1.2;

`LST(10)` : (D=1) not used;

`LST(11)` : (D=0) user input via code-word `'FLONG'`, cf. section 3.1.1;

`LST(12)` : (D=6) `NPYMAX`, maximum flavor used in the sea structure function parametrizations, passed from HERACLES;

`LST(13)` : (D=5) heaviest flavour produced in boson-gluon fusion;

`LST(14)` : (D=4) user input via code-word `'BARYON'`, cf. section 3.1.2;

`LST(15)` : (D=9) choice of the parametrization for parton densities in the nucleon, `NPYMOD`, passed from HERACLES, cf. code-word `STRUCTFUNC`, section 3.1.1;

`LST(16)` : (D=1) choice of the structure function library, passed from HERACLES, cf. code-word `STRUCTFUNC`, section 3.1.1;

`LST(17)` : (D=1) not optional: varying energies of initial particles from event to event;

`LST(18)` : (D=0) not optional: running electromagnetic coupling α and boson masses passed from HERACLES;

`LST(19)` : (D=−10) choice of grid for first-order QCD weights;

`LST(20)` : (D=5) scheme for cut-offs against divergences in the QCD matrix elements;

`LST(21)` : error flag, =0 for properly generated event;

`LST(22)` : (D=1) information about chosen target nucleon in current event (proton);

`LST(23)` : specifies process simulated, passed from HERACLES;

- =2: weak charged current (CC), i.e. $W^{\pm}$ exchange;
- =4: neutral current (NC), i.e. γ/Z^0 exchange;

`LST(24)` : information about first-order QCD process in current event;

- =1: q-event, i.e. no first-order QCD;
- =2: qg-event, i.e. gluon radiation in first-order QCD;
- =3: $q\bar{q}$-event, i.e. boson-gluon fusion in first-order QCD;

`LST(25)` : information about flavor of the struck quark in current event: 1=d, 2=u, 3=s, 4=c, 5=b, −1=$\bar{d}$, −2=$\bar{u}$, −3=$\bar{s}$, −4=$\bar{c}$, −5=$\bar{b}$;

`LST(26)` : entry line in event record of outgoing struck quark. In parton shower case, quark at boson vertex before final state shower;

`LST(27)` : signals split of non-trivial nucleon remnant, cf. `LST(14)`;

- =0: no split, simple diquark or `LST(14)` = 0;
- =1: split into parton and particle, $qq+M$ or $q+B$, occurs when sea (anti)quark removed through the interaction;
- =2: split into quark and diquark, $q+qq$, occurs when a gluon is removed;

`LST(28)` : specifies the frame in which the current event is given with code as for `LST(5)`;

`LST(29)` : specifies azimuthal angle rotation with code as for `LST(6)`;

`LST(30)` : chosen helicity for beam lepton in current event;

`LST(31)` : not optional, fixed by `LST(1)`;

`LST(32)` : for internal use;

`LST(33)` : for internal use;

`LST(34)` : (D=1) used for soft color interaction in LEPTO 6.5.1;

`LST(35)` : (D=1) used for new sea quark treatment in LEPTO 6.5.1;

`LST(36)` – `LST(40)` : (D=0) not used.

PARL(1) : (D=1.) for internal use;
PARL(2) : (D=1.) for internal use;
PARL(3) : (D=0.44) user input via code-word 'KT-PARTON', cf. section 3.1.2;
PARL(4) : (D=0.75) user input via code-word 'DIQUARK', cf. section 3.1.2;
PARL(5) : $\sin^2\theta_W$ (weak mixing angle), passed from HERACLES (SW2);
PARL(6) : polarization of lepton beam, passed from HERACLES (POLARI);
PARL(7) : (D=0.5) used for soft color interaction in LEPTO 6.5.1;
PARL(8), PARL(9) : (D=0.04, 4.) cut-offs against divergences in QCD matrix elements, see the remarks in the LEPTO manual [10];
PARL(10) : not used;
PARL(11) : (D=0.01) required relative accuracy for one-dimensional integration, used for first-order QCD matrix element weights and longitudinal structure function integrals;
PARL(12) : (D=0.01) probability for intrinsic charm;
PARL(13) : (D=0.1) internal parameters used for adjustment of y_{cut} for integration of QCD matrix elements;
PARL(14) : (D=0.35) user input via code-word 'KT-REMNANT', see section 3.1.2;
PARL(15) : (D=0.01) not used;
PARL(16) : finestructure constant α, passed from HERACLES (ALPHA);
PARL(17) : weak Fermi constant G_F, passed from HERACLES (GF);
PARL(18) : Δr from radiative corrections, passed from HERACLES (DELTAR);
PARL(19) : (D=0.03) scale κ^2 in GeV^2 for higher twist correction;
PARL(20) : (D=0.1) used for the treatment of a more complicated nucleon remnant than a simple diquark;
PARL(21) : scaled $\tilde{s}$;
PARL(22) : scaled $\tilde{y}\tilde{s}$ ($= y_h s_h$);
PARL(23) : total cross section in pb, passed from HERACLES (= SIGTOT*10^3);
PARL(24) : Monte Carlo estimate of the cross section in pb associated with the generated event sample. May be reduced as compared to the value of PARL(23) when hadronization of some of the events failed;
PARL(25) : value of α_s in current event;
PARL(26) : value of Λ used in last structure function call, passed from HERACLES (filled only when LST(16) = 1);
PARL(27) : depending on the value of LST(20), present value of the cut variable for first-order QCD;
PARL(28) – PARL(30) : values of x_p, z_q, ϕ in first order massless QCD matrix elements, see LEPTO manual;

X, Y, W2, Q2, U : **rescaled** variables $\tilde{x}$, $\tilde{y}$, $\tilde{W}^2$, $\tilde{Q}^2$, $\tilde{\nu}$, see section 2.2.1. Except for $\tilde{y}$, the rescaled variables are identical to the hadron variables.

1.2.4 Common blocks `DJPASS` and `SPPASS`

`COMMON /DJPASS/ NTOT,NPASS,NFAILL`

Content:	contains statistics of events treated in LEPTO:
Parameters:	
`NTOT` :	Total number of events generated by HERACLES;
`NPASS` :	Number of events which have been hadronized completely in LEPTO;
`NFAILL` :	Number of events which failed hadronization in LEPTO. These events have a hadronic mass above the cut for hadronization in SOPHIA and were identified as candidates for hadronization in LEPTO, but failed there. Their event record is given back at the parton level.

`COMMON /SPPASS/ NSOPH,NSPOUT,NFAILP,NSPACC`

Content:	contains statistics of events treated in SOPHIA:
Parameters:	
`NSOPH` :	Total number of events with successful hadronization in SOPHIA;
`NSPOUT` :	*not used*;
`NFAILP` :	Number of events where hadronization in SOPHIA failed;
`NSPACC` :	Flag to identify events treated by SOPHIA.

1.2.5 Common block HSCHNN

`COMMON /HSCHNN/ ICHNN`

Content:	contains information on the origin of the event from the channels of HERACLES
Parameters:	
`ICHNN` :	flag of channel, passed from HERACLES:
=1:	non-radiative neutral current (NC) event,
=2:	non-radiative charged current (CC) event,
=3:	non-radiative elastic scattering event (EL),
=6:	leptonic initial state photon radiation (NC),
=7:	leptonic final state photon radiation (NC),
=8:	Compton event (NC),
=12:	radiative charged current event (CC),
=15:	quasi-elastic event with initial state radiation,
=16:	quasi-elastic event with final state radiation,
=17:	quasi-elastc event (Compton type).

Appendix A: Definition of kinematical cuts

In the present version of the program the basic constraint on the momentum transfer $Q^2 \geq Q^2_{min}$ is superimposing all further kinematical constraints. Q^2_{min} may be defined by the user via the option 'KINEM-CUTS'. In addition, limits on x and y and a minimal hadronic mass W may be given. Additionally, several definitions of the kinematical region may be requested by the user via the input parameters of the option 'KINEM-CUTS'. In the following we list in detail the kinematical cuts as defined in the program for non-radiative events ($S = 4E_eE_p$).

- ICUT=1 : x-limits and Q^2_{min} from input accepted, y-limits and W_{min} ignored;

$$Q^2_{min} \leq Q^2 \leq Q^2_{max} = x^{input}_{max} \cdot S,$$
$$x_{min} = \mathrm{Max}\{x^{input}_{min}, Q^2_{min}/S\} \leq x \leq x^{input}_{max}.$$

- ICUT=2 : As ICUT=1 with an additional lower cut on the mass of the final state hadrons,

$$W^2_{min} \leq W^2 = (1-x)yS + M^2_P.$$

  W_{min} will be set automatically to M_P if the input is smaller. The additional restriction of W^2 translates into a modification of the lowest allowed Q^2 value in the actual calculation:

$$Q^2_{min} = \mathrm{Max}\left\{(Q^2_{min})^{input}, \frac{x}{1-x}(W^2_{min} - M^2_P)\right\},$$

  and

$$x_{max} = \mathrm{Min}\{x^{input}_{max}, 1 - (W^2_{min} - M^2_P)/S\}.$$

- ICUT=3 : All given limits ($x_{min,max}$, $y_{min,max}$, Q^2_{min}, and W_{min}) are accepted. The actually applied limits are calculated from the most restrictive input conditions resulting in:

$$Q^2_{min} = \mathrm{Max}\left\{x_{min}y_{min}S, (Q^2_{min})^{input}, \frac{x_{min}}{1-x_{min}}(W^2_{min} - M^2_P)\right\} \leq Q^2,$$

$$x_{min} = \mathrm{Max}\{x^{input}_{min}, Q^2_{min}/y_{max}S\},$$

$$x_{max} = \mathrm{Min}\{x^{input}_{max}, 1 - (W^2_{min} - M^2_P)/y_{max}S\},$$

$$y_{min} = \mathrm{Max}\left\{y^{input}_{min}, Q^2_{min}/x_{max}S, \frac{W^2_{min} - M^2_P}{(1-x_{min})S}\right\}.$$

For radiative events, analogous constraints are respected depending on the value of ICUT. In this case the limits on the hadronic final state mass does not change the input values for the cuts on x and y or Q^2, but restricts the phase space of the bremsstrahlung photon.

Appendix B: Conventions for header and final record

Before event generation, a header record is written to the common block /HEPEVT/ with NEVHEP = -1. The content of its first entry (IHEP = 1) is according to the standard [35]. The other entries have the following meaning:

NHEP:	= 73, number of entries in the header record;
PHEP(1,2):	= EELE, energy of the initial electron in GeV;
PHEP(1,3):	= POLARI, polarization of the initial electron;
PHEP(1,4):	= EPRO, energy of the initial proton in GeV;
PHEP(1,5):	= XMIN, minimum of the leptonic x;
PHEP(1,6):	= XMAX, maximum of the leptonic x;
PHEP(1,7):	= YMIN, minimum of the leptonic y;
PHEP(1,8):	= YMAX, maximum of the leptonic y;
PHEP(1,9):	= Q2MIN, minimum of the leptonic momentum transfer Q^2 in GeV^2;
PHEP(1,10):	= WMIN, minimum of the invariant mass of the hadronic final state in GeV;
PHEP(1,11):	= EGMIN, minimum of the photon energy in GeV;
PHEP(1,12):	= MW, W boson mass in GeV;
PHEP(1,13):	= MZ, Z boson mass in GeV;
PHEP(1,14):	= MH, Higgs boson mass in GeV;
PHEP(1,15):	= MT, top-quark mass in GeV;

ISTHEP(2):	= LLEPT, charge of the initial lepton;
ISTHEP(3):	= ICUT, flag for kinematical cuts;
ISTHEP(4:15):	= LPARIN(1:12), flags for the definition of electroweak parameters and partial electroweak corrections;
ISTHEP(16):	= ISTRFC, flag for the parametrization of quark distribution functions or structure functions;
ISTHEP(17):	= NPYMIN, minimal number of flavors;
ISTHEP(18):	= NPYMAX, maximal number of flavors;
ISTHEP(19):	= LUNIN, logical unit number for parameter input;
ISTHEP(20):	= LUNOUT, logical unit number for standard output;
ISTHEP(21):	= LUNTES, logical unit number for test output;
ISTHEP(22):	= LUNRND, logical unit number for in- and output of the random number generator;
ISTHEP(23):	= LUNDAT, logical unit number for in- and output of results of the integration step;
ISTHEP(24):	= NINP, logical unit number for VEGAS input;
ISTHEP(25):	= NOUTP, logical unit number for VEGAS output;
ISTHEP(26:30):	= flags for integration of non-radiative partial cross sections (internally denoted by INT2(1:5);
ISTHEP(26):	= INC2 from input code word 'INT-OPT-NC';

ISTHEP(27): = ICC2 from input code word 'INT-OPT-CC';
ISTHEP(28:30): = not used;
ISTHEP(31:45): = flags for integration of radiative partial cross sections (internally denoted by INT3(1:15);
ISTHEP(31): = INC31 from input code word 'INT-OPT-NC';
ISTHEP(32): = INC32 from input code word 'INT-OPT-NC';
ISTHEP(33): = INC33 from input code word 'INT-OPT-NC';
ISTHEP(34:36): = not used
ISTHEP(37): = ICC31 from input code word 'INT-OPT-CC';
ISTHEP(38): = ICC32 from input code word 'INT-OPT-CC';
ISTHEP(39): = ICC33 from input code word 'INT-OPT-CC';
ISTHEP(40:45): = not used;
ISTHEP(46): = NPOVEG, maximal number of points used in the VEGAS integration;
ISTHEP(47): = NUMINT, not active in version 4.6.4;
ISTHEP(48): = NPHYP, not active in version 4.6.4;
ISTHEP(49:53): = flags for the inclusion of non-radiative partial cross sections in event generation (internally denoted by ISAM2(1:5));
ISTHEP(49): = ISNC2 from input code word 'SAM-OPT-NC';
ISTHEP(50): = ISCC2 from input code word 'SAM-OPT-CC';
ISTHEP(51:53): = not used;
ISTHEP(54:68): = flags for the inclusion of radiative partial cross sections in event generation (internally denoted by ISAM3(1:15));
ISTHEP(54): = ISNC31 from input code word 'SAM-OPT-NC';
ISTHEP(55): = ISNC32 from input code word 'SAM-OPT-NC';
ISTHEP(56): = ISNC33 from input code word 'SAM-OPT-NC';
ISTHEP(57:59): = not used;
ISTHEP(60): = ISCC31 from input code word 'SAM-OPT-CC';
ISTHEP(61): = ISCC32 from input code word 'SAM-OPT-CC';
ISTHEP(62): = ISCC33 from input code word 'SAM-OPT-CC';
ISTHEP(63:68): = not used;
ISTHEP(69): = INTOPT, flag for integration in- or excluding preparation of the sampling step;
ISTHEP(70): = IPRINT, flag for test ouput;
ISTHEP(71): = ISDINP, flag for input of random number seeds;
ISTHEP(72): = ISDOUT, flag for output of random number seeds;
ISTHEP(73): = NEVENT, requested number of events;

The following list shows the content of the final record with NEVHEP = -2. This record contains output of the program.

NHEP: = 44, number of entries in the final record;
PHEP(1,1): = SIGTOT, total cross section;
PHEP(1,2): = SIGTRR, estimated error of the total cross section;

PHEP(1,3:22):	= SIGG(1:20), partial cross sections;
PHEP(1,23:42):	= SIGGRR(1:20), estimated errors of partial cross sections;
PHEP(1,43):	= SW2, weak mixing angle s_W^2;
PHEP(1,44):	= MW, W boson mass; may be changed from its input value;

ISTHEP(1):	= NEVENT, total number of generated events;
ISTHEP(2:22):	= NEVE(1:21), partial event numbers for each channel.

Appendix C: Update history

C.1 HERACLES, version 4.6.7

- For Sophia, in routine `DJGSPH`: status of beam particles on `K(IP1,1)` set to 201 according to convention used in `HSACPT` and elsewhere.

- For Sophia, in routine `DJGSPH`: momentum of virtual boson on event record corrected.

C.1 HERACLES, version 4.6.6

- Value of `PARL(24)` (corrected cross section to take into account possibly reduced phase space due to failing hadronization) is determined in the main program of HERACLES and not any more updated for every event generation step.

- In `djangoh_l.f`, do not allow values for the degree of polarization transfered to `PARL(6)` larger than 0.99 (smaller than -0.99). A corresponding `IF`-statement in `LEPTOX` is made safe against roundoff errors.

- In `HSACPT`, added variable `IDJSPH` to tag events with W below the cutoff for hadronization in SOPHIA. The LEPTO-related routine `HSWCUT` is called only if needed to test for possible fragmentation in LEPTO.

- On common block `DJPASS`, added variable `NFAILL` to count events where hadronization failed in LEPTO. Also, counting on variable `NTOT` is corrected: counts events with successful hadronization in LEPTO. Affects also `djangoh_u.f`.

- On common block `SPPASS`, added variables `NSPACC` to tag successful hadronization in SOPHIA. Affects also `djangoh_u.f`.

- Default of `LST(3)` reduced to 2: only warnings printed, execution stopped on error.

C.2 HERACLES, version 4.6.5

- Following suggestions by V. Lendermann, the code to specify structure functions and parton distribution functions was modified: The variables `IPART` (on common block `HSPARL`) and `NPYMOD` (on common block `HYSTFU`) are not used anymore and are removed from the code. Also `LPAR(6)` is not used anymore. A new common block `HSSTRP` with the three integer variables `ICODE, ILIB, ILQMOD` is introduced and keeps identification code for the structure functions. Input is expected now for these three variables separately after code word `'STRUCTFUNC'` (see section 1.1.1).

- The default value for the infrared cutoff `XIRDEL` used to separate radiative from non-radiative elastic $ep \rightarrow ep(\gamma)$ scattering is increased from 2×10^{-4} to 2×10^{-2}. The consistency check on the value of `XMAX` is modified to take into account this cutoff.

- In `djangoh_l.f`, subroutine `HSWCUT`: corrected name of common block `LYPARA` (was still `PYPARA`.

- The undocumented input variable `IOPLOT` is removed from the list of input data for code word `'TEST-OPT'`.

C.3 HERACLES, version 4.6.4

The program SOPHIA is interfaced to DJANGOH through the new subroutine `DJGSPH`. The new input code word `'SOPHIA'` allows to change the value of the cutoff for the hadronic mass `WSOPHIA` (on common block `SOPHCT`). The default is 1.5 GeV.

C.4 HERACLES, version 4.6.3

- Counters of event numbers in separate channels are now of type `real*8` to avoid overflows.

- Corrected call of `HSRNDM` (missing argument).

- Corrected normalization factor for radiative charged current scattering with polarized positrons in `HSCCKL` and `HSCCQF`.

- Corrected routine `D01AJF` which was used for initialization of non-radiative elastic scattering cross section: now calls function `F` as provided as input argument, not directly `HSELG1`.

- Clean-up of code and output.

C.5 HERACLES, version 4.6.2

The following modifications were made as of August, 28, 1998 in the file `djangoh_h.f`:

- Most of the changes werde made to improve the calculation of radiative contributions for charged current scattering. The subroutine `HSCCKL` has been rewritten and new routines were added (`HSCKMX`, `HSCXSM`, `HSCLAB`, `HSCCMS` and `HSCPHL`).
- In `HSSTDL` the missing declaration for `HSF2DL` was added (thanks to Masahida Inuzuka).
- Variable names containing "`$`" were replaced by "_" (underscore) in `HSSFZZ`.

C.6 HERACLES, version 4.6.1 and DJANGO6, version 2.5

This is an overview of modifications updating HERACLES and DJANGO6 to versions 4.6 and 2.5, resp. Read the manual for further details.

- New channels for the radiative elastic tail, $ep \rightarrow ep\gamma$ are included now. Accordingly, additional input for the code words `'INT-OPT-NC'` and `'SAM-OPT-NC'` is expected and the new code words `'NUCLEUS'` and `'EP-DIPOLE'` were introduced.
- HERACLES and DJANGO6 are now combined in one single program which is run in either HERACLES mode or in DJANGO6 mode. The HERACLES mode is chosen if
  (i) no input for DJANGO6 is given, or
  (ii) `LST(7)` < 0 is given as input to the code word `FRAG`.
  In the HERACLES mode, no calls to DJANGO6 routines are performed and the HERACLES options are allowed. These are in particular: combined NC and CC event generation, low-Q^2 structure functions with `ILQMOD` > 1, quarkonic radiation and interference of radiation from the lepton and the quark line. In DJANGO6 mode only channels for either neutral or charged current processes are allowed and the execution stops if `ILQMOD` > 1. Note also, that a check on whether there is enough hadronic energy in the final state to allow for fragmentation and/or hadronization is performed only in the DJANGO6 mode. Internally, the two different modes are flagged by the variable `IHSONL`.
- An upper limit on Q^2 can be given, the input for code word `'KINEM-CUT'` is expected to contain a corresponding value after `Q2MIN` and before `WMIN`.
- The input option for code word `'HYP-CUBES'` with input item `NPHYP` is activated. It can be used to control the number of function evaluations during the estimation of function maxima. The default value for `NPHYP` has been increased.

- For ILQMOD $= 10$, the program calls the routine FIUSER to calculate user-defined structure functions F_1, F_2.
- The ALLM parametrization for structure functions (ILQMOD $= 3$) has been replaced by the new version [29].
- The low-Q^2 suppression of parton distribution functions has been put into a separate function HSLOQS to allow for more convenient possible future modifications.
- Calls to parton distributions from PAKPDF (ILIB $= 3$) are disabled.
- The new default for parton distributions is ISTRFC $= 123041$, *i.e.* MRS(G) taken from PDFLIB with exponential low-Q^2 suppression.
- According to the range of validity given by the authors, the parametrization of Badełek and Kwiecinski [30] (ILQMOD = 4) is restricted to $x > 10^{-5}$ and execution is stopped if it is requested together with $x_{\min} < 10^{-5}$.
- Events from channel INC33 (Compton events) are not excluded anymore automatically from hadronization. Fragmentation and hadronization is performed if enough hadronic energy is available.
- A new version of the routine HSDQDV (for the calculation of some infrared photonic contributions) should avoid floating point exceptions which appeared for $y_l \to 1$ in the former version.
- The requested accuracies for integration in DX1FCF and VEGAS (EPS0 and ACCVEG) are increased.
- The timer routine LTIMEX is activated.
- The initialization for PYSTFU is corrected, reset MSTU(112) = NPYMAX and e^+ versus e^-.
- The initialization for F_L is made consistent: new routines DIALFS and DIFLOP are used to transfer options and parameters from input to LEPTO and PYTHIA. LST(12) is reset after having been used in HSLUFL.
- The check on negative values F_1 after inclusion of F_L is changed in HSSTR1.
- In HSACPT, the flavor of the struck quark is chosen by calling HSFLAV also for IPDFOP $= 2$, *i.e.* if F_L is included.
- The charged current radiative channel ICC33 (part of the $1/(k \cdot q')$-pole) is disabled since it gave wrong results for small $x < 10^{-2}$.
- Contributions from incoming b quarks to the CC process are excluded (the correct treatment would require threshold factors for the t quark mass).

- The treatment of electron and proton masses in relations of kinematic variables is made consistent ($Q^2 = xy\hat{s}$ with $\hat{s} = 2l \cdot p$ also in the calculation of F_L: `PARL(21)` $= \hat{s}$).
- The definition of `CUT(10)` is corrected (was never used, but when checking consistency of kinematic limits).
- To test whether `IX` is out of range, modifications were done in `HSINIT`.
- Execution is stopped in `HSGENM` if a wrong correction of maxima occurs.
- The `OPEN` statements for data file and file for random number generator seeds are corrected.
- Routines related to the random number generator are renamed, as well as the corresponding common block `/RANDOM/` which became `/HSRNDC/`.
- `D01FCF` is renamed to `DX1FCF`.
- `NFLMAX`, the number of trials for fragmentation in LEPTO is increased to 10.
- The initialization of ARIADNE is corrected.
- The true $W_{\min}$ is used when printing a warning on a reduced cross section written to `PARL(24)`.
- A write statement in routine `LWEITS` of LEPTO is corrected.
- The output header and many other format statements are changed.
- Two commented lines with a call to a test routine `TSTRRR` locate the place where the initialization of HERACLES/DJANGO6 is completed. `TSTRRR` can be used, for example, to produce a listing of values of structure functions and other intermediate results.

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